Characteristics Analysis of Voltage Sag in Distribution System using RMS Voltage Method

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***Abstract*—Voltage sags caused by the short-circuit faults in transmission and distribution lines have become one of the most important power quality problems facing industrial customers and utilities. Voltage sags are normally described by characteristics of both magnitude and duration, but phase-angle jump should be taken into account in identifying sag phenomena and finding their solutions. In this paper, voltage sags due to power system faults such as three-phase-to-ground, single phase-to-ground, phase-to-phase, and two-phase-to-ground faults are characterized by using symmetrical component analysis and their effect on the magnitude variation and phase-angle jumps for each phase are examined. A simple and practical method is proposed for voltage sag detection, by calculating RMS voltage over a window of one cycle and one-half cycle. The industrial distribution system at Bajaj hospital is taken as a case study. Simulation studies have been performed by suing MATLAB/SIMULINK and the results are presented at various magnitudes, duration and phase-angle jumps.**

***Index Terms*—Power quality, voltage sag, characterization, rms detection, point-on-wave**

I. Introduction

According to IEEE standard 1159-1995, a voltage sag is defined as a decrease in rms voltage down to 90% to 10% of nominal voltage for a time greater than 0.5 cycles of the power frequency but less than or equal to one minute [1]. Voltage sags have always been present in power systems, but only during the past decades have customers become more aware of the inconvenience caused by them [2]. Voltage sag may be caused by switching operations associated with a temporary disconnection of supply, the flow of inrush currents associated with the starting of motor loads, or the flow of fault currents. These events may emanate from the customers system or from the public network. Lighting strikes can also cause voltage sags [3]. The interests in the voltage sags are increasing because they cause the detrimental effects on the several sensitive equipments such as adjustable-speed drives, process-control equipments, programmable logic controllers, robotics, computers and diagnostic systems, is sensitive to voltage sags. Malfunctioning or failure of this equipment can caused by voltage sags leading to work or production stops with significant associated cost [4], [5].

In the conventional method to assess these effects, voltage sags are characterized by its magnitude and duration. The magnitude is defined as the percentage of the remaining voltage during the sag and the duration is defined as the time between the sag commencement and clearing [5]. However, balanced and unbalanced faults not only cause a drop in the voltage magnitude but also cause change in the phase angle of the voltage. Therefore, power-electronics converter that use phase angle information for their firing instants may be affected by the phase angle jump [6], [7]. Electrical contractors were determined to be an example of a device that is extremely sensitive to point-on-wave of sag initiation. Contractors are essentially electromechanical relays and widely used in industry to control electrical devices. In order to find any solutions for voltage sag problems due to faults, it is necessary to identify characteristics of magnitude, duration, point-on-wave and phase angle variations.

RMS (voltage or current) is a quantity commonly used in power systems as an easy way of accessing and describing power system phenomena. The rms value can be computed each time a new sample is obtained but generally these values are updated each cycle or half cycle. If the rms values are updated every time a new sample is obtained, then the calculated rms series is called continuous. If the updating of rms is done with a certain time interval, then the obtained rms is called discrete [7]. The analysis of different voltage sag characteristics of different disturbances, a method using RMS voltage to detect the voltage sag is proposed in this paper. The correctness of the method is proved by simulations.

In this paper, a comprehensive study is presented in order to show the proposed characterization of voltage sags for the three types of faults, SLG, LL, and LLG. The algorithms for voltage sag detection and results by using MATLAB/ SIMULINK software.

II. Voltage Sag Characteristics

Voltage sag is defined as a decrease in rms voltage at the power frequency for durations of 0.5 cycles to 1 minute. This definition specifies two important parameters for voltage sag: the rms voltage and duration. The standard also notes that to give a numerical value to a sag, the recommended usage is a sag 70%, which means that the voltage is reduced down to 70% of the normal value, thus a remaining voltage of 30%. Sag magnitude is defined as the remaining voltage during the event. The power systems faults not only cause a drop in voltage magnitude but also cause change in the phase-angle of the voltage. The parameters used to characterize voltage

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sag are magnitude, duration, point-on-wave sag initiation and phase angle jump.

A. Voltage Sag Magnitude

The magnitude of voltage sag can determine in a number of ways. The most common approach to obtain the sag magnitude is to use rms voltage. There are other alternatives, e.g. fundamental rms voltage and peak voltage. Hence the magnitude of the sag is considered as the residual voltage or remaining voltage during the event. In the case of a three-phase system, voltage sag can also be characterized by the minimum RMS-voltage during the sag. If the sag is symmetrical i.e. equally deep in all three phases, if the sag is unsymmetrical, i.e. the sag is not equally deep in all three phases, the phase with the lowest remaining voltage is used to characterize the sag [8].

The magnitude of voltage sags at a certain point in the system depends mainly on the type and the resistance of the fault, the distance to the fault and the system configuration. The calculation of the sag magnitude for a fault somewhere within a radial distribution system requires the point of common coupling (pcc) between the fault and the load. Fig.1 shows the voltage divider model. Where Z_S is the source impedance at the pcc and Z_F is the impedance between the pcc and the fault. In the voltage divider model, the load current before as well as during the fault is neglected. There is no voltage drop between the load and the pcc. The voltage sag at the pcc equals the voltage at the equipment terminals, the voltage sag can be found from the (1).

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} E \tag{1}$$

We will assume that the pre-event voltage is exactly 1 pu, thus E = 1. This result in the following expression for the sag magnitude

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} \tag{2}$$

For fault closer to the pcc the sag becomes deeper small Z_F). The sag becomes deeper for weaker supplies (larger *Zs*) [6].

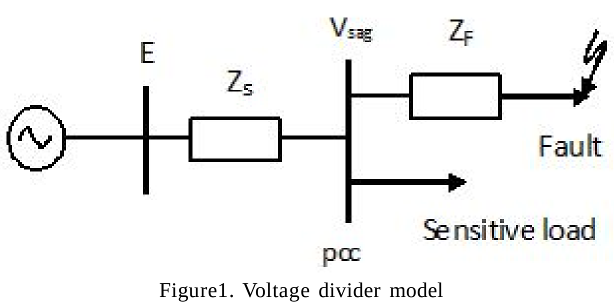

Figure1. Voltage divider model

B. Voltage Sag Duration

The duration of voltage sag is mainly determined by the fault–clearing time. The duration of a voltage sag is the amount of time during which the voltage magnitude is below threshold is typically chosen as 90% of the nominal voltage magnitude. For measurements in the three-phases systems the three rms voltages have to be considered to determine duration of the sag. The voltage sag starts when at least one of the rms voltages drops below the sag-starting threshold. The sag ends when all three voltages have recovered above the sag-ending threshold [9].

Graphically, this definition of the sag duration is shown in Fig. 4(b).

C. Phase Angle Jump

A short circuit in a power system not only causes a drop in voltage magnitude but also a change in the phase angle of the voltage. In a 50 Hz system, voltage is a complex quantity which has magnitude and phase angle. A change in the system, like a short circuit, causes a change in voltage. This change is not limited to the magnitude of the voltage but includes a change in phase angle as well. The phase angle jump manifests itself as a shift in zero crossing of the instantaneous voltage. Phase-angle jumps are not of concern for most equipment. But power electronics converters using phase-angle information for their firing instants may be affected.

To understand to origin of phase-angle jumps associated with voltage sags, the single-phase voltage divider model of Fig. 1 can be used again, with the difference that Z_S and Z_F are complex quantities which we will denote as $\bar{Z}_S$ and $\bar{Z}_F$. The expression for voltage sag at pcc can be express as

$$\bar{V}_{sag} = \frac{\bar{Z}_F}{\bar{Z}_S + \bar{Z}_F} \tag{3}$$

Let $\bar{Z}_S = R_S + jX_S$ and $\bar{Z}_F = R_F + jX_F$ are the sources and feeder impendence respectively. In this paper the pre-event voltage is assumed 1 pu, thus E=1. Then the phase angle jump in the voltage is given by the following expression.

$$\Delta\phi = \arg(\bar{V}_{sag})$$

$$\Delta\phi = \arctan\left(\frac{X_F}{R_F}\right) - \arctan\left(\frac{X_S + X_F}{R_S + R_F}\right) \tag{4}$$

If $\frac{X_S}{R_S} = \frac{X_F}{R_F}$, expression (4) is zero and there is no phase-angle jump. The phase-angle jump will thus be present if the X/R ratios of the source and the feeder are different [6], [10].

D. Point on Wave

To obtain a accurate value for the sag duration one needs to be able to determine “start” and “ending” of the sag with a higher precision. For this one needs to find the so-called “point-on-wave of sag initiation” and the “point-on-wave of voltage recovery”.

The point-on-wave initiation is the phase angle of the fundamental wave at which the voltage sag starts. This angle corresponds to the angle at which the short-circuit fault occurs. As most faults are associated with a flashover, they are more likely to occur near voltage maximum than voltage zero. Point on wave initiation and ending are phase angles at which

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instantaneous voltage starts and ends to experience reduction in voltage magnitude, i.e. between which the corresponding rms voltage is below the defined threshold limit (usually defined as 90% and 10% of the nominal voltage, respectively). Point-on-wave initiation corresponds to phase angle of the pre-sag voltage, measured from the last positive-going zero crossing of the pre-sag voltage, at which transition from the pre-sag to during sag voltage is initiated. Similarly, point-on-wave of ending corresponds to phase angle of the post-sag voltage. Measured with respect to the positive-going zero crossing of the post-sag voltage, at which transition from during-sag to post-sag voltage, respectively, and not to during-sag voltage is to avoid complications introduced by the phase shifts and transients that usually occur at the sag initiation and at the sag ending. Both point-on-wave values are usually expressed in degrees or radians [6], [11].

III. Method of Voltage Sag Detection with Rms Value Algorithm

The magnitude of voltage sag can be determined in a number of ways, most existing monitors obtained the sag magnitude from the RMS voltages. There are several alternative ways of quantifying the voltage level. Two obvious are the magnitude of the fundamental component of the voltage and the peak voltage over each cycle or half-cycle. As long as the voltage is sinusoidal, it does not matter whether RMS voltage, fundamental voltage, or peak voltage is used to obtain the sag magnitude. But the RMS voltage, related to power calculation, make it more suitable for the characterization of the magnitude of voltage sags. For continuous periodic signals, the RMS value is defined as

$$V_{rms} = \sqrt{\frac{1}{2}\int_{t_0}^{t_0+T} v^2(t)dt} \tag{5}$$

where T is the period of the signal.

According to the definition of root mean value, the RMS voltage over one data window typically one cycle is done by using the following discrete integral equation.

$$V_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} vi^2} \tag{6}$$

Real RMS is obtained if the window length N is set to one cycle. In practical application, the data window is sliding along the time sequence in specific sample interval. In order to distinguish each result, time instant stamps labeled K are added to RMS voltage as independent variable i.e., it makes RMS voltage to be a function of time.

Rewrite the (6) to the sequence, shown as follows

$$V_{rms(k)} = \sqrt{\frac{1}{N}\sum_{i=k-N+1}^{i=k} vi^2} \qquad k\ e\text{”}\ 1 \tag{7}$$

$$Vrms(k) = Vrms(N), \qquad k < N \text{ and } k\ e\text{”}\ 1$$

The time stamp k is restricted to be an integer that is equal to or greater than 1. Each value from (7) is obtained over the processing window. It is obvious that the first (N-1) RMS voltage values have been made equal to the value for sample N. It is due to data window limitation and data truncation and couldn’t be avoided. In (6) the time instant matching is determined by the integral discretizing process. The above equation makes the result to the last sample point of the window. The determination of initialization time and recovery time of the disturbances will be affected by time matching, while the duration will not.

If the RMS voltage value calculation is integrated voltage waveform decomposition, the above equation could be a byproduct of voltage signal FFT processing.

Meanwhile some power quality monitors are due to some certain reasons; the calculation of voltage rms values is calculated once every cycle but not each sample point interval window-sliding just like before expressions. The expression each window sliding is shown as follows:

$$V_{rms(kN)} = \sqrt{\frac{1}{N}\sum_{i=(k-1)N+1}^{kN} vi^2} \quad V_{rms(kN)} = \sqrt{\frac{1}{N}\sum_{i=(k-1)N+1}^{kN} vi^2}$$

$$K \geq 1 \tag{8}$$

It is very likely that the power quality monitor will give one value with an intermediate before its voltage rms value made. It is valuable when obtaining disturbance duration such as voltage sags.

In practice, there is no extra computing cost comparing (7) to (8), i.e. the costs are same almost. The latter can be considered to be sub-sampled or down-sampled from (7) result sequence in *(N-1)* interval. The information capacity and required achieving space is the only two differences in nature when they are saved or transferred to the databases of the power quality centre. The tips for implementation of (7) can be described as following, which has considered the window sliding:

First, take every sample point to the power 2; then, declare three global variables, which represent the value of the first point, the last point and the total sum over the N point’s window respectively. When the window is sliding to a new position in the interval of one sample point, update the last point value, then the total sum with the expressing: the sum (new) = the sum (old) + the last point(new) - the first point (old), and update the first point. Finally, take the N divide and square root operation to the sum value, then make a next slide to start a new circle. The data window length used in (7) and (8) can theoretically be any integer number of half-cycles. It is recommended that the window length of equation (8) should be as shorter as possible for enough information keeping [12].

A shorter window than one half-cycle is not useful. The window length has to be an integer multiple of one half-cycle. Any other window length will produce an oscillation in the result with a frequency equal to twice the fundamental frequency [6]. A great advantage of this method is its sim

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plicity, speed of calculation and less requirement of memory, because RMS can be stored periodically instead of sample per sample. However, its dependency on window length is considered a disadvantages, one cycle window length will give better results in terms of profile smoothness than a half cycle window at the cost of lower time resolution.

Moreover RMS does not distinguish between fundamental frequency, harmonics or noise components, therefore the accuracy will depend on the harmonics and noise content. When using RMS technique phase angle information is lost [6].

A. RMS Value Evaluation Method

RMS values continuously calculated for a moving window of the input voltage samples provide a convenient measure of the magnitude evolution, because they express the energy contents *N* samples per cycle (or half-cycle). The resulting RMS value at sampling instant *k* can be calculated by

$$V_{rms}[k] = \sqrt{\frac{1}{N}\sum_{i=0}^{N-1} v^2[k-i]} \tag{9}$$

suppose

$$S[k-1] = \sum_{i=0}^{N-1} v^2[k-i] \tag{10}$$

then

$$S[k-1] = \sum_{i=0}^{N-1} v^2[k-i-1] \tag{11}$$

from (9) and (10)

$$S[k] - S[k-1] = \sum_{i=0}^{N-1} v^2[k-i] - \sum_{i=0}^{N-1} v^2[k-i-1] \tag{12}$$

$$= v^2[k-i] - v^2[k-N] \tag{13}$$

So,

$$S[k] = v^2[k] - v^2[k-N] + S[k-N] \tag{14}$$

Fig. 2 illustrates a Z-domain representation for the voltage rms magnitude evaluation using moving window. The basic idea is to follow the voltage magnitude changes as close the disturbing event. The more rms values are calculated, the closer the disturbing event is represented [13].

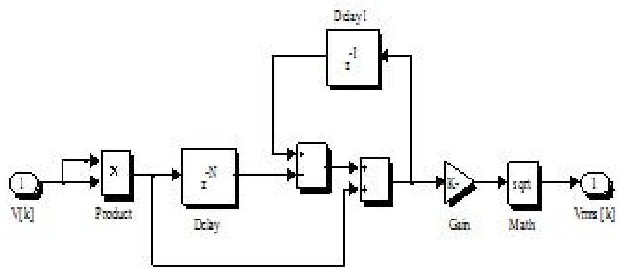

Figure2. RMS value evaluation using a moving window

IV. Simlation Model

A. Fault System Model

A simulation model as shown in Fig. 3 is the express feeder for Bajaj hospital under study. It is fed from 33/11 kv distribution substation of Maharashtra State Distribution Company Limited (MSEDCL), Railway station, Industrial area, Aurangabad, India has been consider for voltage sag analysis. The system is modeled using the simulink and SimpowerSystem utilities of MATLAB. Table I. shows system parameters used in the simulation.

The performance study of sample system is carried out for detection and characterization of voltage due to power system faults. It is assumed that a fault has occurred on the primary side of distribution transformer T2, and the fault lasted for 4 cycles from t = 0.045 to 0.125 seconds. The monitoring equipment is installed at the pcc.

Table I. Distribution System Parameters

Component	Details
Source	10 MVA, 33 kv X/R=10
Transformer T1	5 MVA, 33/11 kv, %Z=7.15, X/R=10, DYn11
Transformer T2	750 KVA, 11/0.433 kv, %Z=5, X/R=6, DYn11
Line	0.6748+j0.372/km, 2km
Load	190 kw, 130Kkvar
Frequency	50 Hz

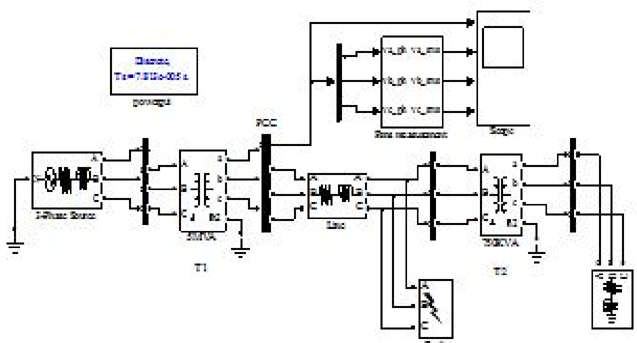

Figure3.Simulink model of test system

V. Simulation Results and Discussion

A. Single phase-to-Ground Fault

For simulation it is assumed that a single phase fault has appeared on phase A. The instantaneous voltages wave-form, rms voltages, and their phase angles are shown in Fig. 4.

Both the fault and the monitor are located in same 11 kv distribution system.

The waveform shown in Fig. 4(a) shows an overvoltage at the end of the sag in faulted phase A. This overvoltage is almost certainly related to the cause of the fault. The voltage of phase A drops nearly zero, while phases B and C voltages normally remains at pre-fault levels as shown in Fig. 4(b). The algorithm for calculating the RMS voltage has been

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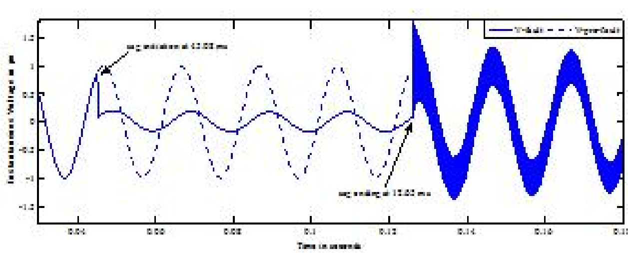
applied to the voltage sag shown in Fig. 4(b), where solid line indicates the one-cycle and dashed line half-cycle RMS voltage. The Fig. 4(b) shows that the half-cycle algorithm is faster to detect the starting and ending of the voltage sag. The half-cycle rms shows a faster transition, thus showing that the recovery actually takes place in two stages. The estimation of sag duration is not much different and do not affect the sag estimation.

Fig. 4(a) shows the voltage sag where the transition takes place on the zero-crossing and there is no distortion during the sag. This voltage sag has a remaining magnitude of 0.18 pu and has a duration of 4-cycles. By employing the moving-window RMS computation technique, Fig. 4(b) is obtained. It is clear by examination of Fig. 4(a) that the sag has about 4-cycle steady-state. The transition to the sag is sharp at the zero crossing. RMS plot shows slow a one-cycle transition before reaching the 0.18 pu value and a one-cycle rise to recovery. This slow transition is due to the moving window retaining almost one cycle of "historical" information in the calculation.

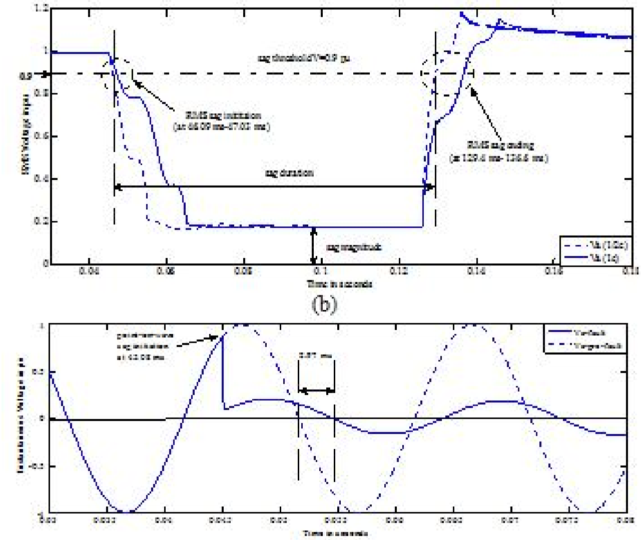
The voltage drops on phase A is upto 0.18 pu of the nominal voltage, and one-cycle (solid line) half-cycle (dashed line) sliding windows, the corresponding 'RMS duration' of the voltage sag from Fig. 4(b) are 89.57 ms and 83.31 ms, respectively. During the sag the voltage in the faulted phase Va is suppressed with a large phase-angle jump, whereas the phase-angle jump in the other two non-faulted phases is almost not affected. The one with the maximum absolute value is chosen for the index of single-phase in single-phase event. It is (- 48.92) degrees in this case. The point-on-wave of sag initiation is where the voltage suddenly drops in value. The point indicates the starting instants of the fault as shown in Fig. 4(C). We see that the point-on-wave of sag initiation is about (61.92) degree.

B. Phase-to-phase Fault

The phase-to-phase faults also cause voltage sag. Fig. 5 shows the voltage waveform, rms voltage for one and half-cycle and phase-angle jump for phase voltages due to phase-to-phase fault between phases B and C. In Fig. 4(a) and Fig. 4(b), magnitudes and phase angles of phases B and C, with a large voltage drop in the two phases Vb and Vc but phase voltage Va remains unchanged. The phase voltages drop in magnitude Vb = 0.6 and Vc = 0.4 pu, The duration of voltage sag phases B and C are 88.47 ms, 92.89 ms and 81.55ms, 89.8 ms for one cycle and half-cycle respectively. The phase–angle jumps are (+ 47.88) and (- 42.12) degree.



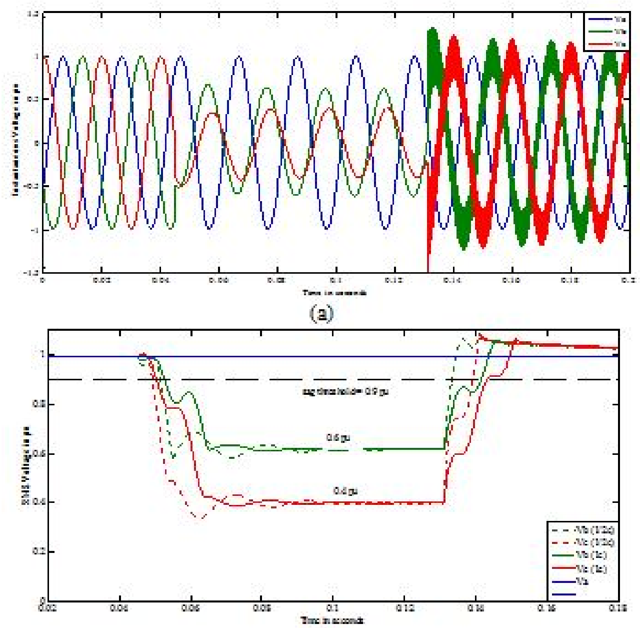
(a)



(b)

(c)

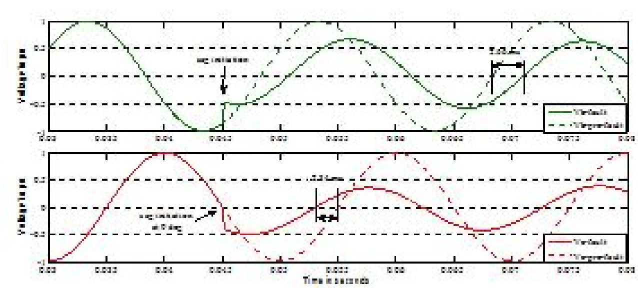
Figure 4. Single-phase-to-ground fault (a) Instantaneous voltage waveform, (b) RMS voltage sag magnitude, (solid line for one cycle and dashed line for half-cycle) (c) Phase-angle jump and point-on-wave sag initiation



(a)

(b)

Figure5. Phase-to-phase fault, (a) Three-phase voltage waveform, (b) RMS voltage sag magnitude for phase A, B and C (solid line for one cycle and dashed line for half-cycle).



(c)

Figure5. Single-phase-to-ground fault, (c) Phase-angle jump and point-on-wave sag initiation.

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C. Two-Phase-to-ground Fault

A voltage sag due to a two-phase-to-ground fault between phases B, C and ground. The voltage waveform, rms voltages for one and half-cycle, point-on-wave sag initiation and phase-angle jump are recorded at the pcc as shown in Fig. (6). This shows a significantly large drop in rms voltage in the faulted phases B and C, but no change in phase A. The phase voltages drop in magnitude, voltage sag duration for one and half-cycle, point-on-wave sag initiation and their phase-angle jumps are given in the table II.

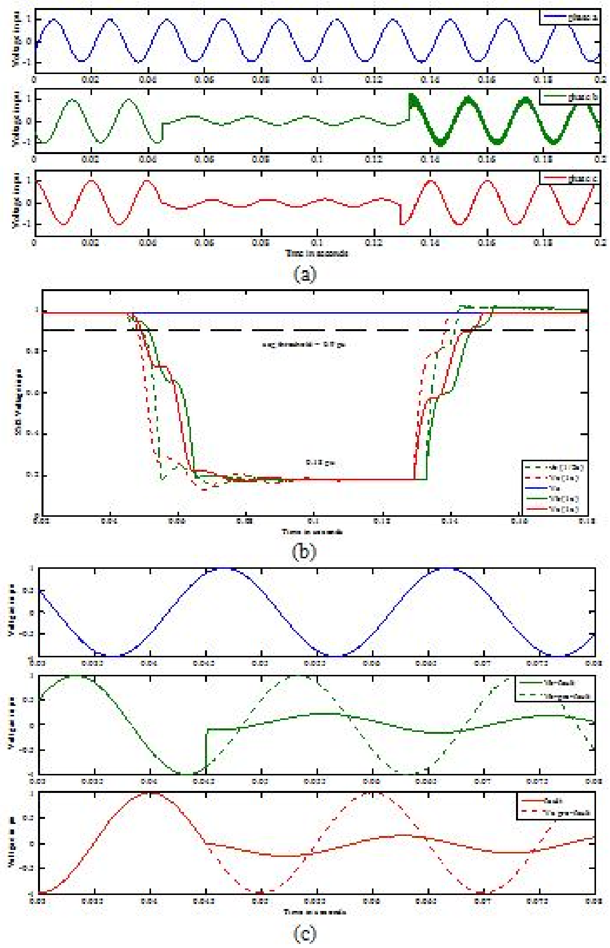

Figure6. Two-Phase-to-ground fault (a) Three-phase voltage waveform; (b) RMS voltage sag magnitude for phase A, B and C; (c) Phase-angle jumps for phase A, B and C

Table II. Shows the simulation results obtain from the unbalanced faults, for fault duration t = 0.045 to t = 0.125

TABLE II. SIMULATION RESULT

Faults	phases	Volta-ge sag magni-tude [p.u]	Phase angle jump [deg]	Point on wave sag initiation [deg]	Sag duration by RMS 1-cycle [ms]	½-cycle [ms]	Difference [ms]
SLGF	A	0.18	+53.46°	61.92°	89.57	83.31	6.26
LLF	B	0.6	+47.88°	122.4°	88.84	81.55	7.29
	C	0.4	- 42.12°	0°	92.89	89.8	3.09
LLGF	B	0.18	- 57.60°	120.96°	94.25	92.58	1.67
	C	0.18	- 63.36°	0°	94.8	90.07	4.73

VI. CONCLUSIONS

Voltage sags have been mainly characterized by magnitude and duration. This paper presents a broad voltage sag characterization in terms of sag magnitude, sag duration and phase-angle jump by using MATLAB/SIMULINK software has been applied to practical distribution system at Bajaj hospital feeder. Simulation result has been presents in terms of the magnitude, duration and phase-angle jump due to three phase-to-ground, single phase-to-ground, phase-to-phase and two phase-to-ground faults. This value enables a prediction of the fault of the event on most single-phase and three-phase equipment. When more detailed characterization of the event is required, additional parameters can be added for three-phase balanced and unbalanced voltage sags.

The effective value or RMS is basically an averaging technique that relies on the periodicity and the sine-wave nature of the waveform for making comparisons. RMS loses its conventional worth if the periodicity and sine wave shape features are lost, i.e if the waveform becomes nonstationary. Because of its computational method, it is essentially insensitive to polarity changes and less sensitive to phase shifts. RMS computations are widely used for classifying voltage sag magnitude and duration. The phase-angle jump, estimated from instantaneous voltage values using discrete Fourier transformation.

This broader sag characterization is intended to improve the estimation of load tolerance and reduce investments on sag mitigation.

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